JC564 U.S. PTO
03/03/98

Schlumberger Oilfield Services

Anadrill Wireline & Testing
Sugar Land Product Center
110 Schlumberger Drive, Sugar Land, TX 77478
P. O. Box 2175, Houston, Texas 77252-2175
(281) 285 8500
(281) 285 4232 Fax

Assistant Commissioner for Patents
Box Patent Application
Washington, DC 20231

Docket No. 24.787
Total Pages 171

Re: Application of: Bruno Luong et al.
For: Nuclear Magnetic Resonance Apparatus and Method for Generating an Axisymmetric Magnetic Field Having Straight Contour Lines in the Resonance Region
Full Names of Inventor(s): Bruno Luong, Krishnamurthy Ganesan, and Martin E. Poitzsch

__X__ 37 CFR 1.53(b) UTILITY PATENT APPLICATION TRANSMITTAL, or

______ 37 CFR 1.53(b) CONTINUING APPLICATION OF PRIOR APPLICATION NO. __/__________

[ ] Continuation
[ ] Divisional
[ ] Continuation-in-part (CIP)

In accordance with 37 CFR 153(b) enclosed are:

1 [X] Fee Transmittal Form (Original & Duplicate)
2 [X] Patent Application Total No. Pages 29
3a [X] Informal Drawings Total No. Pages 13
3b [ ] Formal Drawings Total No. Pages ____
4 [X] Oath or Declaration Total No. Pages 3
4a [ ] Newly Executed (Original or Copy)
4b [ ] Copy from Prior Application (37 CFR 1.63(d)) for Continuation/Divisional noted above
4c [ ] Deletion of Inventors (Signed Statement Deleting Inventors Named in Prior Application 37 CFR 1.63(d)(2) and 1.33(b)
5 [ ]Incorporation by Reference (Usable if 4b is checked) Entire Disclosure of Prior Application, from which a copy of the oath for declaration is supplied is considered as being part of the disclosure of the accompanying application and is hereby incorporated by reference therein
6 [ ] Amend the specification by inserting before the first line the sentence: This is a [ ] continuation [ ] continuation-in-part [ ] division of application serial no. __________ filed __________.
7 [ ] The prior application is assigned to SCHLUMBERGER TECHNOLOGY CORPORATION.

Accompanying Application Parts

6 [X] Assignment Papers (Cover Sheet & document(s))
7 [ ] 37 CFR 3.73(b) Statement
[ ] Power of Attorney
8 [X] Information Disclosure Statement (IDS)PTO-1449
[ ] Copies of Citations
9 [ ] Preliminary Amendment
10 [X] Return Receipt Postcard (MPEP 503)
11 [ ] English Translation Document
12 [ ] Certified Copy of Priority Document (if Foreign Priority is Claimed)
13 [ ] Other: ____________

CLAIMS AS FILED				
(1) FOR	(2) NUMBERS FILED	(3) NUMBER EXTRA	(4) RATE	(5) TOTAL
BASIC FEE				$790
TOTAL CLAIMS	42-20=	22	x$22	$484
INDEPENDENT CLAIMS	6-3=	3	x$82	$246
ADDITIONAL FEE FOR FILING ONE OR MORE MULTIPLE DEPENDENT CLAIMS $270				
TOTAL FILING FEE				$1520
RECORDING FEE	[X] SEE ATTACHED PTO 1595 [ ] ASSIGNMENT TO BE SUBMITTED LATER			

Please charge Deposit Account No. 19-0610 for the above written total amount and any additional fees or credit any over-payment to Deposit Account No. 19-0610.

Please send all correspondence to the following correspondence address: Office of Patent Counsel, Schlumberger Oilfield Services, P.O. Box 2175, Houston, TX 77252-2175.

"EXPRESS MAIL" Mailing Label
Number EI165494210US
Date of Deposit March 3, 1998
I hereby certify that this paper or fee is being deposited with the United States Postal Services "Express Mail Post Office to Addressee" Service under 37 C.F.R. 1.10 on the date indicated above and is addressed to the Assistant Commissioner for Patents, Washington, DC 20231

Respectfully Submitted,

Signature:
Name: Brigitte L. Jeffery
Reg. No.: 38,925
Date: February 27, 1998

NUCLEAR MAGNETIC RESONANCE APPARATUS AND METHOD FOR GENERATING AN AXISYMMETRIC MAGNETIC FIELD HAVING STRAIGHT CONTOUR LINES IN THE RESONANCE REGION

Background of the Invention

The present invention relates generally to an apparatus and method for measuring nuclear magnetic resonance properties of an earth formation traversed by a borehole, and more particularly, to an apparatus and method for generating a substantially axisymmetric static magnetic field having long, straight contour lines in the resonance region.

It is well recognized that particles of an earth formation having non-zero nuclear spin magnetic moment, for example protons, have a tendency to align with a static magnetic field imposed on the formation. Such a magnetic field may be naturally generated, as is the case for the earth's magnetic field, B_E. After an RF pulse applies a second oscillating magnetic field B_1, transverse to B_E, the protons will tend to precess about the B_E vector with a characteristic resonance or Larmor frequency ω_L which depends on the strength of the static magnetic field and the gyromagnetic ratio of the particle. Hydrogen nuclei (protons) precessing about a magnetic field B_E of 0.5 gauss, for example, have a characteristic frequency of approximately 2kHz. If a population of hydrogen nuclei were made to precess in phase, the combined magnetic fields of the protons can generate a detectable oscillating voltage, known to those skilled in the art as a free induction decay or a spin echo, in a receiver coil. Hydrogen nuclei of water and

hydrocarbons occurring in rock pores produce nuclear magnetic resonance (NMR) signals distinct from signals arising from other solids.

U.S. Pat. Nos. 4,717,878 issued to Taicher et al. and 5,055,787 issued to Kleinberg et al., describe NMR tools which employ permanent magnets to polarize hydrogen nuclei and generate a static magnetic field, B_0, and RF antennas to excite and detect nuclear magnetic resonance to determine porosity, free fluid ratio, and permeability of a formation. The atomic nuclei align with the applied field, B_0, with a time constant of T_1. After a period of polarization, the angle between the nuclear magnetization and the applied field can be changed by applying an RF field, B_1, perpendicular to the static field B_0, at the Larmor frequency $f_L = \gamma B_0/2\pi$, where γ is the gyromagnetic ratio of the proton and B_0 designates the static magnetic field strength. After termination of the RF pulse, the protons begin to precess in the plane perpendicular to B_0. A sequence of refocusing RF pulses generates a sequence of spin-echoes which produce a detectable NMR signal in the antenna.

U. S. Pat. No. 5,557,201 describes a pulsed nuclear magnetism tool for formation evaluation while drilling. The tool includes a drill bit, drill string, and a pulsed nuclear magnetic resonance device housed within a drill collar made of nonmagnetic alloy. The tool includes a channel, within the drill string and pulsed NMR device, through which drilling mud is pumped into the borehole. The pulsed NMR device comprises two tubular magnets, which are mounted with like poles facing each other, surrounding the channel, and an antenna coil mounted in an exterior surface of the drill string between the

magnets. This tool is designed to resonate nuclei at a measurement region known to those skilled in the art as the saddle point.

Great Britain Pat. App. No. 2 310 500, published on August 27, 1997, describes a measurement-while-drilling tool which includes a sensing apparatus for making nuclear magnetic resonance measurements of the earth formation. The NMR sensing apparatus is mounted in an annular recess formed into the exterior surface of the drill collar. In one embodiment, a flux closure is inserted into the recess. A magnet is disposed on the outer radial surface of the flux closure. The magnet is constructed from a plurality of radial segments which are magnetized radially outward from the longitudinal axis of the tool. The flux closure is required to provide suitable directional orientation of the magnetic field.

The tools developed in the prior art have disadvantages which limit their utility in nuclear magnetic resonance logging applications. Magnet designs of prior art tools do not simultaneously produce a highly axisymmetric static magnetic field with long straight contour lines in the resonance region of the formation under evaluation. These factors adversely affect the NMR measurement given the vertical motion of a wireline tool and the vertical and lateral motion of a logging-while-drilling tool.

Summary of the Invention

The above disadvantages of the prior art are overcome by means of the subject invention for an apparatus and method for generating a substantially axisymmetric static magnetic field having long, straight contour lines in the resonance region. A wireline or logging-while-drilling apparatus within a borehole traversing an earth formation

determines a formation characteristic by obtaining a nuclear magnetic resonance measurement. The apparatus produces a static magnetic field, B_0, into the formation such that the contour lines generated by the static magnetic field are substantially straight in the axial direction at the depth of investigation where the nuclear magnetic resonance measurement is obtained. An oscillating field, B_1, is produced in the same region of the formation as the static magnetic field to obtain the NMR measurement. The apparatus includes at least one magnetically permeable member for focusing the static magnetic field. The magnetically permeable member minimizes variations of the static magnetic field in the formation due to vertical motion of the apparatus while obtaining the nuclear magnetic resonance measurement. Further, the magnetically permeable member may minimize variations of the static magnetic field in the formation due to lateral motion of the apparatus while obtaining the nuclear magnetic resonance measurement. In addition, the magnetically permeable member can add significant prepolarization by causing the B_0 field to have substantial magnitude well ahead of the actual region of investigation which can permit increased logging speed.

The static magnetic field is produced using either an axial, radial, or bobbin magnet design. For the axial design, the static magnetic field is produced by an upper magnet surrounding the carrying means and a lower magnet surrounding the carrying means and axially separated from the upper magnet by a distance such that the contour lines generated by the static magnetic field are substantially straight in the axial direction at the depth of investigation where the nuclear magnetic resonance measurement is obtained. The magnets are axially magnetized giving a radially polarized B_0 field in the region of investigation. At least one magnetically permeable member for shaping the

static magnetic field is located between the lower magnet and the upper magnet. The static magnetic field has either a low gradient or a high gradient, depending on the separation of the magnets, at the depth of investigation where the nuclear magnetic resonance measurement is obtained.

For the radial design, the static magnetic field is produced by an annular cylindrical array of magnets surrounding the carrying means. The array of magnets comprises a plurality of segments, each segment is magnetized in a direction radially outward from and perpendicular to the longitudinal axis of the apparatus. The magnetically permeable member comprises a section of the carrying means, a chassis surrounding a section of the carrying means, or a combination of the chassis and the carrying means section.

For the bobbin design, the static magnetic field is produced by a plurality of geometrically and axisymmetric magnet rings surrounding the carrying means. The plurality of rings comprises an upper ring, a plurality of inner rings, and a lower ring. The radius of the upper and lower rings is greater then the radius of each inner ring. Each of the plurality of rings is axisymmetrically polarized and the direction of polarization for each ring differs progressively along the ring of magnets. The polarization direction of the upper ring is radially opposite to the polarization direction of the lower ring. The polarization of each inner ring changes progressively such that an angle between the polarization and a transverse radius vector varies linearly for each inner ring.

Brief Description of the Drawings

The advantages of the present invention will become apparent from the following description of the accompanying drawings. It is to be understood that the drawings are to be used for the purpose of illustration only, and not as a definition of the invention.

In the drawings:

Fig. 1 illustrates a nuclear magnetic resonance logging-while-drilling tool;

Fig. 2 depicts the low gradient magnet design;

Figs. 2a-2d illustrate the contour lines $|\vec{B}_0|$ corresponding to four low gradient magnet configurations;

Figs. 3a-3d represent the contour lines of the gradient $|\nabla\vec{B}_0|$ corresponding to four low gradient magnet configurations;

Fig. 4 depicts the high gradient magnet design;

Fig. 4a represents the contour lines $|\vec{B}_0|$ corresponding to the high gradient magnet configuration;

Fig. 4b represents the contour lines of the gradient $|\nabla\vec{B}_0|$ corresponding to the high gradient magnet configuration;

Fig. 5 depicts the bobbin magnet design;

Fig. 5a represents the contour lines $|\vec{B}_0|$ corresponding to the bobbin magnet configuration with a non-magnetically permeable member;

Fig. 5b represents the contour lines $|\vec{B}_0|$ corresponding to the bobbin magnet configuration with a magnetically permeable member;

Fig. 6 depicts the radial magnet design;

Fig. 6a represents the contour lines $|\vec{B}_0|$ corresponding to the radial magnet configuration with a non-magnetically permeable member; and

Fig. 6b represents the contour lines $|\vec{B}_0|$ corresponding to the radial magnet configuration with a magnetically permeable member;

Fig. 7 depicts a combination magnet arrangement using three magnets; and,

Fig. 7a represents the contour lines $|\vec{B}_0|$ corresponding to a combination low gradient-low gradient magnet arrangement.

Detailed Description of the Preferred Embodiment

Referring to Fig. 1, a nuclear magnetic resonance (NMR) logging-while-drilling tool **10** is illustrated. The tool **10** includes a drill bit **12**, drill string **14**, a magnet array **16**, RF antenna **18**, and electronic circuitry **20** housed within the drill collar **22**. A means for drilling a borehole **24** in the formation comprises drill bit **12** and drill collar **22**. The mud flow sleeve **28** defines a channel **30** for carrying the drilling fluid through the drill string **14**. A drive mechanism **26** rotates the drill bit **12** and drill string **14**. This drive mechanism is adequately described in U. S. Pat. No. 4,949,045 issued to Clark et al., the disclosure of which is incorporated by reference into this specification. However, it is also within contemplation of the subject invention to use a downhole mud motor placed in the drill string as the drive mechanism **26**.

The magnetic field generated by magnet array **16** is focused by at least one magnetically permeable member **36** positioned inside the drill collar. With this arrangement, member **36** can extend a considerable length in the axial direction without decreasing the mechanical strength of the drill collar **22**. Furthermore, if member **36** consists of a mechanically weak material, a separate, underlying mud flow sleeve **28** provides a degree of protection from the pressure, cuttings, and abrasion of drilling mud. Placement of member **36** outside the drill collar **22** would significantly weaken the mechanical integrity of the tool since that arrangement requires cutting a recessed area from the outside of the drill collar to accommodate member **36** thereby weakening collar **22** due to the section of drill collar between channel **30** and the recess having a decreased thickness in comparison to other sections of the drill collar. It is within contemplation of the subject invention that the magnetically permeable member **36** comprises a segment **38** of sleeve **28**. In this case, an additional layer of space is not required inside the drill collar for member **36** and the available space is sufficient to accommodate a magnet array having a larger volume.

Low Gradient Design

Referring to Fig. 2, in a preferred embodiment of the invention, hereinafter referred to as the low gradient design, magnet array **16** comprises an upper magnet **32** axially separated from a lower magnet **34**. The area between magnets **32, 34** is suitable for housing elements such as electronic components, an RF antenna, and other similar items. Both magnets **32, 34** surround sleeve **28**. A magnetically permeable member **36** is positioned inside the drill collar **22** between the magnets **32, 34**. Member **36** may consist of a single piece or a plurality of sections combined between the magnets. Member **36** is

constructed of a suitable magnetically permeable material, such as ferrite, permeable steel or another alloy of iron and nickel, corrosion resistant permeable steel, or permeable steel having a structural role in the member design, such as 15-5 Ph stainless steel. The magnetically permeable member **36** focuses the magnetic field and either carries drilling fluid through the drill string or provides structural support to the drill collar. Further, member **36** improves the shape of the static magnetic field generated by magnets **32**, **34** and minimizes variations of the static magnetic field due to vertical and lateral tool motion during the period of acquisition of the NMR signal. The segment **38** of sleeve **28** between magnets **32**, **34** may comprise magnetically permeable member **36**. In this case, the segments **40**, **42** of sleeve **28** under magnets **32**, **34** shall consist of a non-magnetic member. Alternatively, a magnetically permeable chassis **44** surrounding segment **38** defines member **36**. In this case, segment **38** may consist of a magnetic or non-magnetic material. It is within contemplation of this invention to integrate chassis **44** and segment **38** to form member **36**.

The magnets **32**, **34** are polarized in a direction parallel to the longitudinal axis of the tool **10** with like magnetic poles facing each other. For each magnet **32**, **34**, the magnetic lines of induction travel outward from an end of the magnet **32**, **34** into the formation to create a static field parallel to the axis of the tool **10** and travel inward to the other end of the magnet **32**, **34**. In the region between upper magnet **32** and lower magnet **34**, the magnetic lines of induction travel from the center outward into the formation, creating a static field in the direction perpendicular to the axis of the tool **10**. The magnetic lines of induction then travel inward symmetrically above the upper magnet **32** and below the lower magnet **34** and converge in the longitudinal direction inside sleeve

28. Because of the separation, the magnitude of the static magnetic field in the central region between the upper **32** and lower **34** magnet is relatively homogeneous. The amount of separation between the magnets **32, 34** is determined by selecting the requisite magnetic field strength and homogeneity characteristics. As the separation between the magnets **32, 34** decreases, the magnetic field becomes stronger and less homogeneous. Conversely, as the separation between the magnets **32, 34** increases, the magnetic field becomes weaker and more homogeneous.

Figs. 2a-2d illustrate the contour lines of $|\vec{B}_0|$ corresponding to four configurations of upper **32** and lower **34** magnets. The configuration corresponding to Fig. 2a comprises a non-magnetically permeable member separating an upper **32** and lower **34** magnet by 25 inches. The configuration corresponding to Fig. 2b comprises a non-magnetically permeable member separating an upper **32** and lower **34** magnet by 18 inches. The configuration corresponding to Fig. 2c comprises a non-magnetically permeable member separating an upper **32** and lower **34** magnet by eight inches. The low gradient design, corresponding to Fig. 2d, comprises a magnetically permeable member **36** separating an upper **32** and lower **34** magnet by 25 inches. Figs. 3a-3d represent the contour lines of the gradient $|\nabla\vec{B}_0|$ corresponding respectively to configurations illustrated in Figs. 2a-2d.

In the low gradient design, a significant portion of the magnetic flux is shunted by the magnetically permeable member **36** into the center of the tool **10**. To illustrate, the magnitude of the B_0 field shown in Fig. 2d at a distance of approximately seven inches radially from the longitudinal axis of tool **10** is twice as large as the B_0 field shown in

Fig. 2a which was generated by the same magnet configuration separated by a non-magnetically permeable member. Furthermore, the low gradient design produces a longer and more uniform extent of the static magnetic field in the axial direction. The NMR signal measured in this embodiment is substantially less sensitive to the vertical motion of the tool. Referring to Fig. 3d, with the low gradient design, a relatively small, approximately 3 Gauss/cm, gradient is measured at a distance of approximately seven inches radially from the longitudinal axis of tool. This low gradient results in a measured NMR signal which is substantially less sensitive to the lateral motion of the tool **10**. Moreover, with the low gradient design, the proton rich borehole region surrounding the tool **10** will resonate only at frequencies higher than those being applied to the volume of investigation, i.e., there is no borehole signal. This is a characteristic of all embodiments of this invention. Other NMR sensitive nuclei found in drilling mud, such as sodium-23, resonate at significantly higher static magnetic field strengths than hydrogen when excited at the same RF frequency. These higher field strengths are not produced in the borehole region surrounding the tool or near the antenna where such unwanted signals could be detected. This is a characteristic of the axial magnet designs of this invention, including the high gradient design.

<u>High Gradient Design</u>

As previously described, with the low gradient design, a significant portion of the magnetic flux is shunted by the magnetically permeable member **36** into the center of the tool **10**. Without the shunting of magnetically permeable member **36**, a high gradient design is achieved by separating the upper **32** and lower **34** magnet to obtain the same

$|\vec{B}_0|$ illustrated in Fig. 2d. As shown in Fig. 2b, a magnetic field strength, 60 Gauss, at a distance of approximately seven inches radially from the longitudinal axis of tool **10**, is achieved by a non-magnetically permeable member separating the magnets **32**, **34** by 18 inches. However, the shape of the volume of investigation in which the static magnetic field strength is in resonance with the RF frequency remains curved, and the field contour lines are relatively short in the axial direction. Furthermore, the receiver for detecting the NMR signal is sensitive to the borehole signal, as indicated by the two separate magnetic field regions shown in Fig. 2b.

For a high gradient design using a non-magnetically permeable member, the curved shape of the volume of investigation and the borehole signal are overcome by decreasing the separation between magnets **32** and **34**. As illustrated in Fig. 2c, if the magnet separation is decreased to approximately eight inches, the contour lines of the static magnetic field strength become straighter and the strength of $|\vec{B}_0|$ increases. However, the gradient $|\nabla\vec{B}_0|$ becomes larger, as illustrated in Fig. 3c, at a distance of approximately seven inches radially from the longitudinal axis of the tool. The contour lines of $|\nabla\vec{B}_0|$ are curved denoting variation of the gradient in the axial direction.

Referring to Fig. 4, the high gradient design is improved by inserting a magnetically permeable member **36** between magnets **32**, **34**. Fig. 4a represents contour lines of $|\vec{B}_0|$ corresponding to a configuration where magnetically permeable member **36** separates the upper **32** and lower **34** magnets by eight inches. The contour lines of Fig. 4a show less curvature in the axial direction than the contour lines of Fig. 2c. Also, as

illustrated in Fig. 4b, the magnetically permeable member **36** produces a more constant gradient $\left|\nabla \vec{B}_0\right|$ in the axial direction.

Bobbin Design

Referring to Fig. 5, in a second embodiment of the invention, hereinafter referred to as the bobbin design, magnet array **16** comprises a geometrically and magnetically axisymmetric array of magnets **40** surrounding sleeve **28**. Preferably, sleeve **28** is constructed of a suitable magnetically permeable material, such as ferrite, permeable steel or another alloy of iron and nickel, corrosion resistant permeable steel, or permeable steel having a structural role in the member design, such as 15-5 Ph stainless steel. However, it is within contemplation of the subject invention to have a non-magnetically permeable sleeve. The magnet array **40** comprises a ring of magnets **43, 44, 45, 46, 47,** and **48**. The radius of the uppermost ring **47** and the lowermost ring **48** is greater than the plurality of rings **43, 44, 45, 46** defining a central array **42**. The area between rings **47** and **48** can accommodate a deep RF antenna mounted on the drill collar **22**.

With the bobbin design, each ring of the array **40** is axisymmetrically polarized but the directions of polarization differ progressively along the array **40**. The polarizations of the uppermost ring **47** and the lowermost ring **48** are oriented such that their respective lines of extension intersect in the NMR measurement zone of investigation in the formation. Consequently, the orientations of the magnetization of rings **47** and **48** are radially opposite to each other. By way of example, Fig. 5 illustrates the orientation of ring **47** directed outward into the formation and the orientation of ring **48** directed inward. Progressing away from uppermost ring **47**, the polarization of each

ring **43**, **44**, **45**, **46** is tipped and changes progressively in a manner such that the angle between the polarization and the transverse radius vector varies linearly for each ring in the central array **42**. With the bobbin design, the path of magnetic lines of induction travels outward, away from the upper ring **47**, into the formation to create a static magnetic field parallel to the axis of the borehole at the center of the tool **10** and travels inward, towards the lower ring **48**.

Referring to Fig. 5b, the magnet configuration depicted in Fig. 5, used in conjunction with a magnetically permeable sleeve **28**, produces a longer and more uniform static field in the axial direction. The contour lines of $|\vec{B}_0|$ depicted in Fig. 5b are straighter in the middle of the tool **10** than the contour lines of $|\vec{B}_0|$ illustrated in Fig. 5a. Also, the magnetically permeable sleeve of the subject invention permits the magnet array **34** to generate a stronger field at the same location in the formation in comparison to the magnet array **34** surrounding a non-magnetically permeable sleeve. The increased strength of the static field significantly improves the signal-to-noise ratio and enhances the depth of investigation.

<u>Radial Design</u>

Referring to Fig. 6, in a third embodiment of the invention, hereinafter referred to as the radial design, magnet array **16** comprises an annular cylindrical magnet array **50** surrounding a segment **38** of sleeve **28**. The magnet array **50** is comprised of a plurality of segments, each segment is magnetized radially, that is, outward from the longitudinal axis of the tool **10**. Such a magnet array is described in U. S. Pat. No. 4,717,876 to Masi et al., for example. An antenna **52** is mounted in an exterior recess **54** of the drill collar

22. A non-conductive, magnetically permeable layer of material **56**, such as ferrite, fills recess **54**. The antenna **52** also surrounds sleeve **28**. The RF magnetic field, B_1, generated by current flowing through antenna **52** has field directions substantially parallel to the longitudinal axis of the tool **10**. Alternatively, the RF magnetic field, B_1, is generated by an array of antennas and B_1 extends azimuthally about the longitudinal axis of the tool **10**.

Still referring to Fig. 6, magnetically permeable member **36** is comprised of segment **38**. Similar to the low gradient design, a chassis surrounding segment **38** may define the permeable member **36**. For illustrative purposes only, the radial design described herein refers to a magnetically permeable member **36** consisting of segment **38** constructed of a suitable magnetically permeable material, such as ferrite, permeable steel or another alloy of iron and nickel, corrosion resistant permeable steel, or permeable steel having a structural role in the sleeve design, such as 15-5 Ph stainless steel. The use of a magnetically permeable material for the segment **38** improves the shape of the static magnetic field generated by magnet array **50** and minimizes variations of the static magnetic field due to vertical tool motion during the period of acquisition of the NMR signal. The direction of the static field is illustrated by vectors. The path of the magnetic lines of induction travels from the central section of the magnet array **50** outward into the formation creating a static magnetic field in the direction perpendicular to the borehole axis, travels inward symmetrically above and below the magnet array **50** through segment **38**, and then converges in the longitudinal direction inside sleeve **28**, returning to the central section of the magnet array **50**. The magnetically permeable material forces the return magnetic lines of induction to be more orthogonal to the axial direction when crossing the outer surface of segment **38**. Figs. 6a and 6b compare the field strength of the

array of magnets **50** surrounding a non-magnetically permeable segment **38** versus the field strength of the array of magnets **50** surrounding a magnetically permeable segment **38**.

Referring to Fig. 6a, with a non-magnetically permeable segment **38**, the magnetic energy is primarily concentrated at the extremities of the cylindrical array of magnets **50**. This heterogeneity characteristic of B_0 extends into the surrounding formation. The portions of the static field near the ends of the array **50** are larger than the field located in the middle of the tool **10**. The shape of the formation volume in which the static magnetic field strength is in resonance with the RF frequency is curved, and the field contour lines are relatively short in the axial direction.

Referring to Fig. 6b, with a magnetically permeable sleeve **28**, a longer and more uniform static field is generated in the axial direction. The contour lines of $|\vec{B}_0|$ depicted in Fig. 6b are straighter in the middle of the tool **10** than the contour lines of $|\vec{B}_0|$ illustrated in Fig. 6a. The magnetically permeable sleeve **28** serves a dual purpose of focusing the magnetic field and carrying the drilling fluid through the drill string. Also, the magnetically permeable sleeve of the subject invention permits the magnet array **50** to generate a stronger field at the same location in the formation in comparison to the magnet array **50** surrounding a non-magnetically permeable sleeve. For example, as illustrated in Fig. 6a, the magnetic field strength is 50 Gauss where r = 6" and z = 5". In contrast, as illustrated in Fig. 6b, with a magnetically permeable sleeve, the magnetic field strength increases to 200 Gauss where r = 6" and z = 5". The increased strength of

the static field significantly improves the signal-to-noise ratio of the NMR measurement and enhances the depth of measurement investigation.

It is within contemplation of the subject invention to generate a static magnetic field by combining N+1 magnet arrays **16** to obtain at least N regions of investigation in the formation. The combinations contemplated by this invention include, but are not limited to, a low gradient-low gradient, high gradient -high gradient, high gradient -low gradient, or low gradient -high gradient combination of arrays **16**. By way of example, Fig. 7 illustrates a first low gradient magnet array in combination with a second low gradient magnet array. In the region between upper magnet **60** and central magnet **62**, the magnetic lines of induction travel from the center outward into outward into formation creating a first static field in the direction perpendicular to the axis of the tool **10**. In the region between central magnet **62** and lower magnet **64**, the magnetic lines of induction travel from the center outward into outward into formation creating a second static field in the direction perpendicular to the axis of the tool **10**. Fig. 7a illustrates the contour lines of $|\vec{B}_0|$ corresponding to a configuration where a first magnetically permeable member separates upper magnet **60** and central magnet **62** by approximately 25 inches and a second magnetically permeable member separates central magnet **62** and lower magnet **64** by approximately 25 inches.

The low gradient, high gradient, bobbin, and radial magnet designs of the present invention are also useful in a wireline logging tool application. Sleeve **28** would define a tubular member within the wireline tool which provides structural strength to the tool. Where sleeve **28** is the magnetically permeable member, the sleeve is designed to

withstand substantial axial forces exerted on the tool during fishing operations. If sleeve **28** is the magnetically permeable member, the sleeve can be used for magnetic shielding of electronics, such as electromagnetic relays, that must be within the high magnetic field region produced by the nearby magnets. Moreover, member **36** can be used for the magnetic shielding.

The foregoing description of the preferred and alternate embodiments of the present invention has been presented for purposes of illustration and description. It is not intended to be exhaustive nor to limit the invention to the precise form disclosed. Obviously, many modifications and variations will be apparent to those skilled in the art. The embodiments were chosen and described in order to best explain the principles of the invention and its practical application thereby enabling others skilled in the art to understand the invention for various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the accompanying claims and their equivalents.

What I Claim Is:

1. An apparatus for generating a magnetic field, comprising:

   a) a drilling means for drilling a borehole into the formation;

   b) a means for carrying drilling fluid through the drilling means;

   c) a measuring means, connected to the drilling means, for making nuclear magnetic resonance measurements while the borehole is being drilled, the measuring means comprising:

      i) a means for producing a substantially axisymmetric static magnetic field through the drilling means and into the formation, the static magnetic field producing means comprising:

         a) an array of magnets surrounding the carrying means; and,

      ii) a means for producing an oscillating field in the formation; and,

   d) at least one magnetically permeable member located inside the drilling means for shaping the static magnetic field.

2. The apparatus of claim 1, wherein the array of magnets is annularly cylindrical.

3. The apparatus of claim 2, wherein the array of magnets comprises a plurality of segments, each segment is magnetized in a direction radially outward from and perpendicular to the longitudinal axis of the apparatus.

4. The apparatus of claim 3 wherein the magnetically permeable member in combination with the static magnetic field producing means generates a long, uniform magnetic field in the axial direction.

5. The apparatus of claim 4 wherein the magnetically permeable member comprises a section of the carrying means.

6. The apparatus of claim 4 wherein the magnetically permeable member comprises a chassis surrounding a section of the carrying means.

7. The apparatus of claim 5 wherein the magnetically permeable member further comprises a chassis surrounding the section of the carrying means.

8. An apparatus for generating a magnetic field, comprising:

   a) a drilling means for drilling a borehole into a formation;

   b) a means for carrying drilling fluid through the drilling means;

   c) a measuring means, connected to the drilling means, for making nuclear magnetic resonance measurements while the borehole is being drilled, the measuring means comprising:

      i) a means for producing a substantially axisymmetric static magnetic field through the drilling means and into the formation, the static magnetic field producing means comprising:

         a) a geometrically and magnetically axisymmetric plurality of rings surrounding the drill fluid carrying means wherein the plurality of rings further comprises: a central ring array, an upper ring located above the central ring array, and a lower ring located below the central ring array, each ring is axisymmetrically polarized and the direction of polarization for each ring differs progressively along the plurality of rings; and,

      ii) a means for producing an oscillating field in the formation.

9. The apparatus of claim 8, wherein a section of the carrying means is comprised of a magnetically permeable material.

10. The apparatus of claim 8 further comprising a deep, recessed area on the drilling means between an uppermost magnet of the upper array and a lowermost magnet of the lower array.

11. The apparatus of claim 8, wherein the central ring array comprises a plurality of inner rings wherein the polarization of each inner ring changes progressively such that an angle between the polarization and a transverse radius vector varies linearly for each inner ring.

12. The apparatus of claim 8 wherein the polarization direction of the upper ring is radially opposite to the polarization direction of the lower ring.

13. An apparatus for generating a magnetic field, comprising:

a) a drilling means for drilling a borehole into the formation;

b) a means for carrying drilling fluid through the drilling means;

c) a measuring means, connected to the drilling means, for making nuclear magnetic resonance measurements while the borehole is being drilled, the measuring means comprising:

i) a means for producing a substantially axisymmetric static magnetic field through the drilling means and into the formation, the static magnetic field producing means comprising:

a) an axially magnetized upper magnet surrounding the carrying means; and,

b) an axially magnetized lower magnet surrounding the carrying means and axially separated from the upper magnet by a distance such that the contour lines generated by the static magnetic field are substantially straight in the axial direction at the depth of investigation where the nuclear magnetic resonance measurement is obtained; and,

ii) a means for producing an oscillating field in the formation.

14. The apparatus of claim 13 further comprising at least one magnetically permeable member for shaping the static magnetic field located within the drilling means between the lower magnet and the upper magnet.

15. The apparatus of claim 14 wherein at least one magnetically permeable member is comprised of a section of the drill fluid carrying means.

16. The apparatus of claim 14 wherein at least one magnetically permeable member is comprised of a chassis surrounding the drill fluid carrying means.

17. The apparatus of claim 15 wherein at least one magnetically permeable member is comprised of a chassis surrounding the section of the drill fluid carrying means.

18. The apparatus of claim 13 further comprising a region between the upper magnet and the lower magnet for locating electronics.

19. The apparatus of claim 13 wherein a static magnetic field having a low gradient is generated at the depth of investigation where the nuclear magnetic resonance measurement is obtained.

20. The apparatus of claim 13 wherein a static magnetic field having a high gradient is generated at the depth of investigation where the nuclear magnetic resonance measurement is obtained.

21. An apparatus for generating a magnetic field, comprising:

a) a housing;

b) a measuring means, located inside the housing, for making nuclear magnetic resonance measurements, the measuring means comprising:

i) a means for producing a substantially axisymmetric static magnetic field through the housing and into the formation such that the contour lines generated by the static magnetic field are substantially straight in the axial direction at the depth of investigation where the nuclear magnetic resonance measurement is obtained;

ii) a means for producing an oscillating field in the formation; and,

c) at least one magnetically permeable member for shaping the static magnetic field.

22. The apparatus of claim 21 wherein the means for producing the static magnetic field comprises a plurality of segments surrounding the permeable member, each segment is magnetized in a direction radially outward from and perpendicular to the longitudinal axis of the apparatus.

23. The apparatus of claim 21 wherein the means for producing the static magnetic field comprises a geometrically and magnetically axisymmetric plurality of rings surrounding the permeable member wherein the plurality of rings further

comprises: a central ring array, an upper ring located above the central ring array, and a lower ring located below the central ring array, each ring is axisymmetrically polarized and the direction of polarization for each ring differs progressively along the plurality of rings.

24. The apparatus of claim 21 wherein the means for producing the static magnetic field comprises:

a) an axially magnetized upper magnet; and,

b) an axially magnetized lower magnet axially separated from the upper magnet by a distance such that the contour lines generated by the static magnetic field are substantially straight in the axial direction.

25. The apparatus of claim 24 wherein a static magnetic field having a low gradient is generated at the depth of investigation where the nuclear magnetic resonance measurement is obtained.

26. The apparatus of claim 24 wherein a static magnetic field having a high gradient is generated at the depth of investigation where the nuclear magnetic resonance measurement is obtained.

27. An apparatus for generating a magnetic field, comprising:

a) a drilling means for drilling a borehole into the formation;

b) a means for carrying drilling fluid through the drilling means;

c) a measuring means, connected to the drilling means, for making nuclear magnetic resonance measurements while the borehole is being drilled, the measuring means comprising:

i) means for producing a plurality of substantially axisymmetric static magnetic fields through the drilling means and into the formation at a plurality of regions of investigation where the nuclear magnetic resonance measurement is obtained, and such that the contour lines generated by at least one static magnetic field are substantially straight in the axial direction;

ii) means for producing an oscillating field in the formation; and,

d) at least one magnetically permeable member located inside the drilling means for shaping the static magnetic field.

28. The apparatus of claim 27 wherein the means for producing a plurality of substantially axisymmetric static magnetic fields further comprises means for producing a first static magnetic field which comprises an axially magnetized upper magnet surrounding the carrying means and an axially magnetized central magnet surrounding the carrying means and axially separated from the upper magnet by a first distance.

29. The apparatus of claim 28 wherein the means for producing a plurality of substantially axisymmetric static magnetic fields further comprises means for producing a second static magnetic field which comprises the axially magnetized central magnet surrounding the carrying means and an axially magnetized lower magnet surrounding the carrying means and axially separated from the central magnet by a second distance.

30. The apparatus of claim 29 wherein the means for producing the first static magnetic field generates a static magnetic field having a low gradient at a first

region of investigation where the nuclear magnetic resonance measurement is obtained.

31. The apparatus of claim 30 wherein the means for producing the second static magnetic field generates a static magnetic field having a low gradient at a second region of investigation where the nuclear magnetic resonance measurement is obtained.

32. The apparatus of claim 30 wherein the means for producing the second static magnetic field generates a static magnetic field having a high gradient at a second region of investigation where the nuclear magnetic resonance measurement is obtained.

33. The apparatus of claim 29 wherein the means for producing the first static magnetic field generates a static magnetic field having a high gradient at a first region of investigation where the nuclear magnetic resonance measurement is obtained.

34. The apparatus of claim 33 wherein the means for producing the second static magnetic field generates a static magnetic field having a high gradient at a second region of investigation where the nuclear magnetic resonance measurement is obtained.

35. An apparatus for generating a magnetic field, comprising:

a) a housing;

b) a measuring means, located inside the housing, for making nuclear magnetic resonance measurements, the measuring means comprising:

i) means for producing a plurality of substantially axisymmetric static magnetic fields through the housing and into the formation at a plurality of regions of investigation where the nuclear magnetic resonance measurement is obtained , and such that the contour lines generated by at least one static magnetic field are substantially straight in the axial direction;

ii) a means for producing an oscillating field in the formation; and,

c) at least one magnetically permeable member for shaping the static magnetic field.

36. The apparatus of claim 35 wherein the means for producing a plurality of substantially axisymmetric static magnetic fields further comprises means for producing a first static magnetic field which comprises an axially magnetized upper magnet surrounding the permeable member and an axially magnetized central magnet surrounding the permeable member and axially separated from the upper magnet by a first distance.

37. The apparatus of claim 36 wherein the means for producing a plurality of substantially axisymmetric static magnetic fields further comprises means for producing a second static magnetic field which comprises the axially magnetized central magnet surrounding the permeable member and an axially magnetized lower magnet surrounding the permeable member and axially separated from the central magnet by a second distance.

38. The apparatus of claim 37 wherein the means for producing the first static magnetic field generates a static magnetic field having a low gradient at a first

region of investigation where the nuclear magnetic resonance measurement is obtained.

39. The apparatus of claim 38 wherein the means for producing the second static magnetic field generates a static magnetic field having a low gradient at a second region of investigation where the nuclear magnetic resonance measurement is obtained.

40. The apparatus of claim 38 wherein the means for producing the second static magnetic field generates a static magnetic field having a high gradient at a second region of investigation where the nuclear magnetic resonance measurement is obtained.

41. The apparatus of claim 37 wherein the means for producing the first static magnetic field generates a static magnetic field having a high gradient at a first region of investigation where the nuclear magnetic resonance measurement is obtained.

42. The apparatus of claim 41 wherein the means for producing the second static magnetic field generates a static magnetic field having a high gradient at a second region of investigation where the nuclear magnetic resonance measurement is obtained.

09/033965 24.787

ABSTRACT

The present invention is directed to a nuclear magnetic resonance apparatus and method for generating an axisymmetric magnetic field having long, straight contour lines in the resonance region. A magnetically permeable member is used to shape the static magnetic field generated by an array of permanent magnets. The magnetically permeable member minimizes variations of the static magnetic field in the formation due to vertical motion of the apparatus while obtaining a nuclear magnetic resonance measurement. Further, the magnetically permeable member may minimize variations of the static magnetic field in the formation due to lateral motion of the apparatus while obtaining a nuclear magnetic resonance measurement.

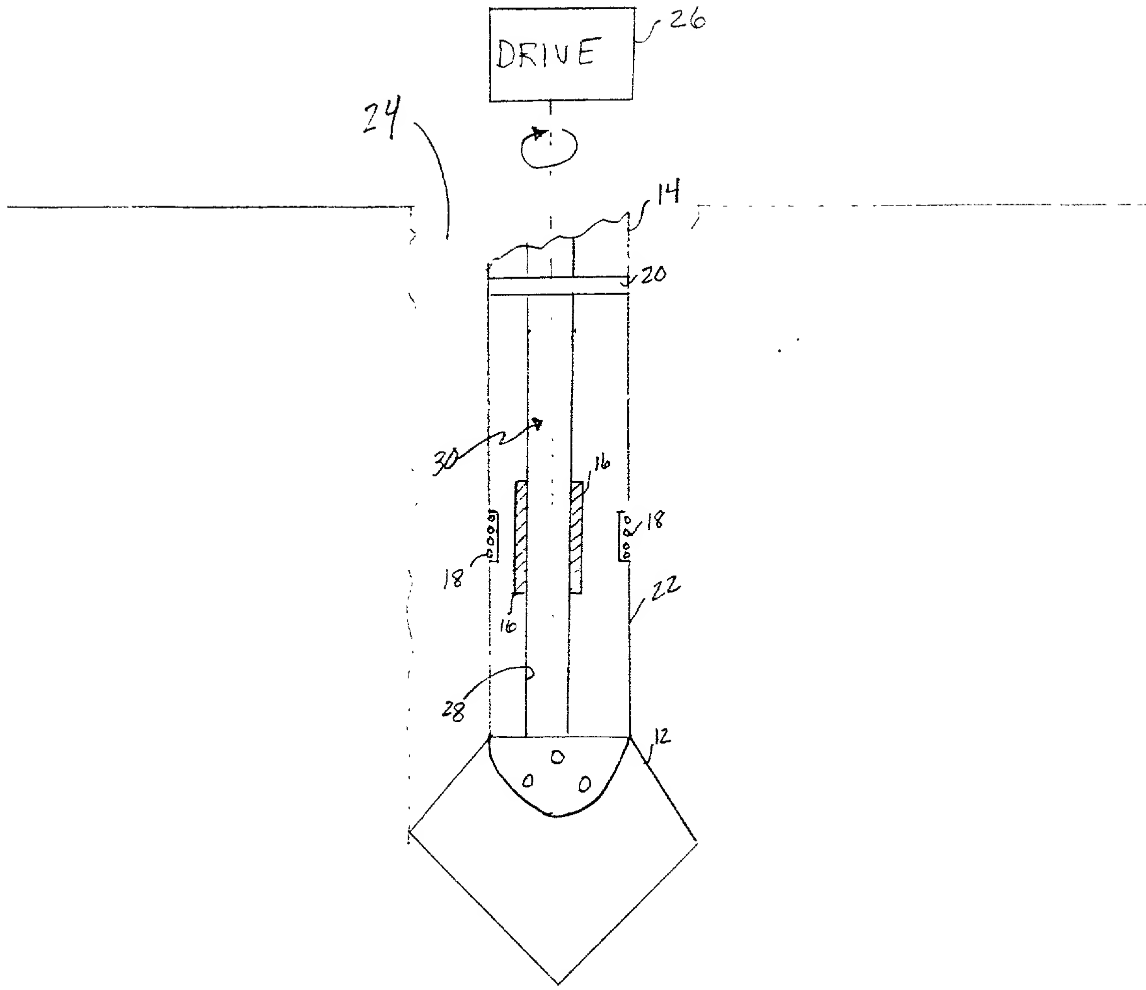


FIG. 1

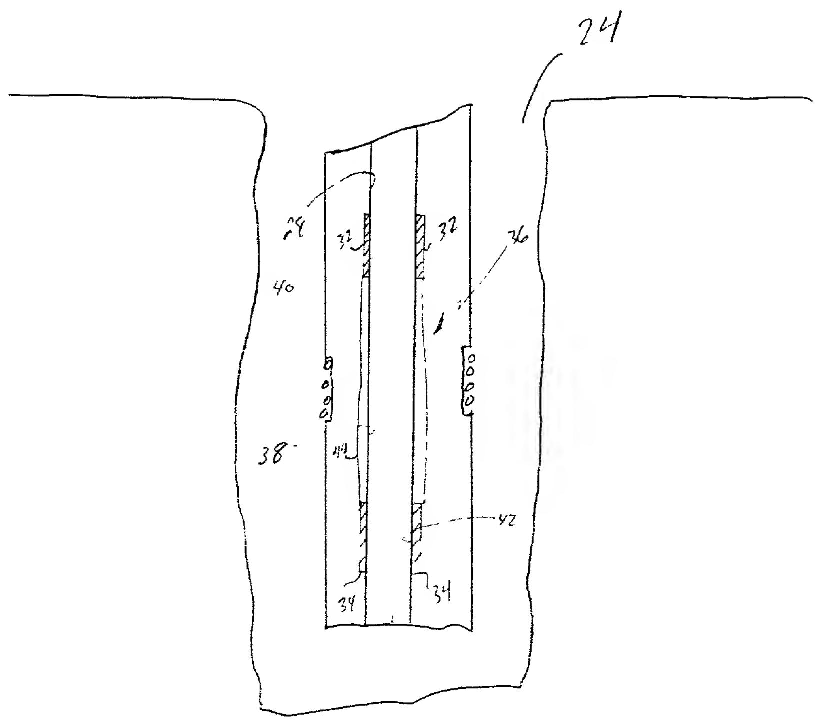


Fig. 2

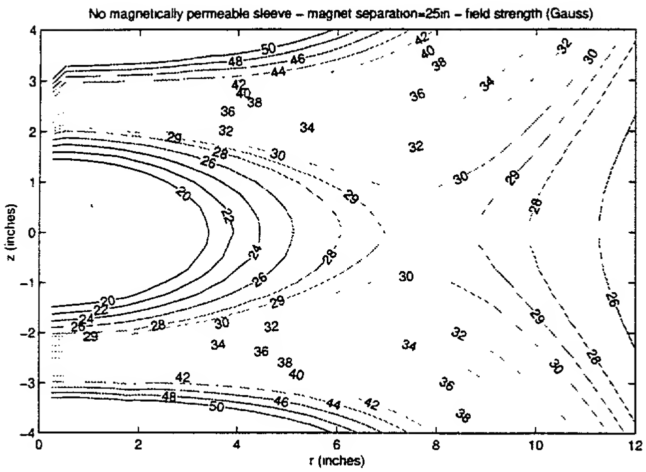


Fig. 2a

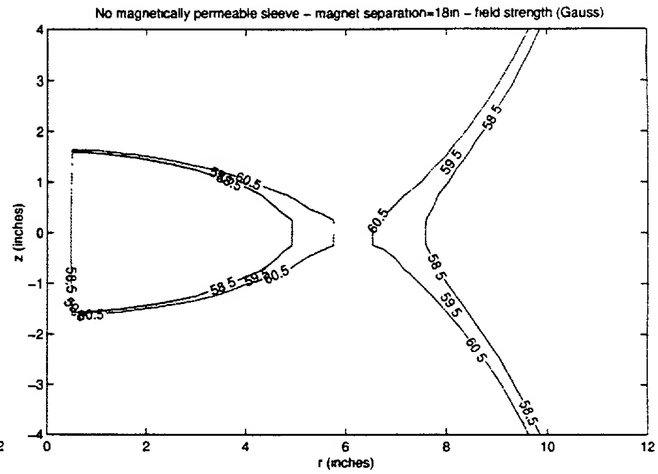


Fig. 2b

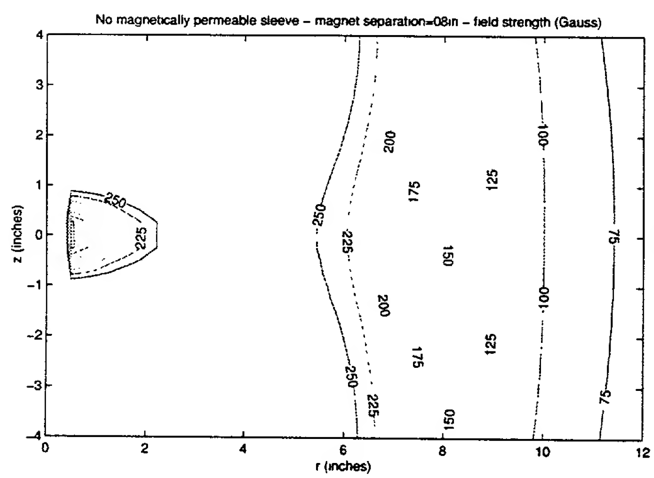


Fig. 2c

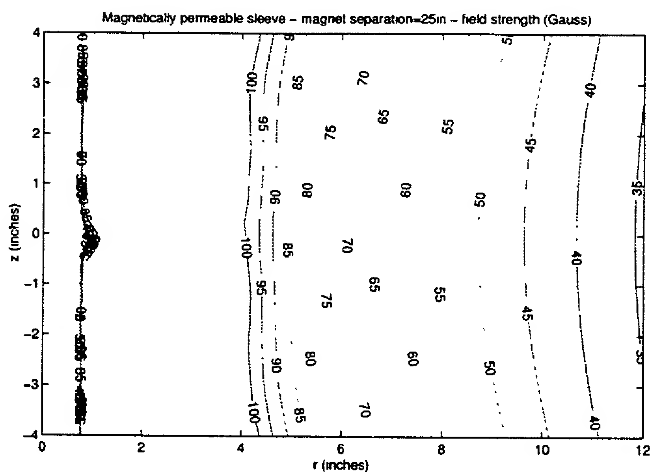


Fig. 2d

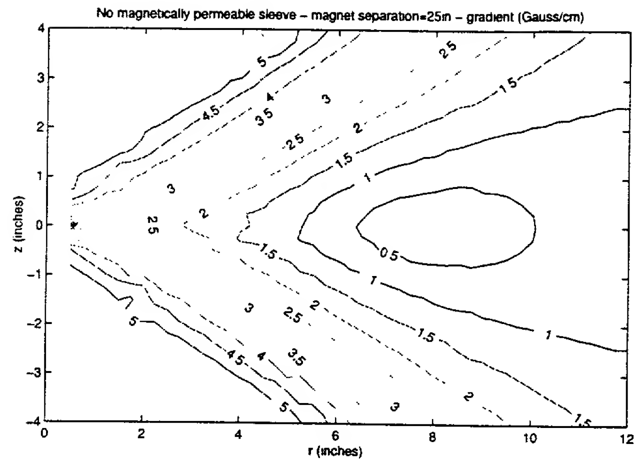


Fig. 3a

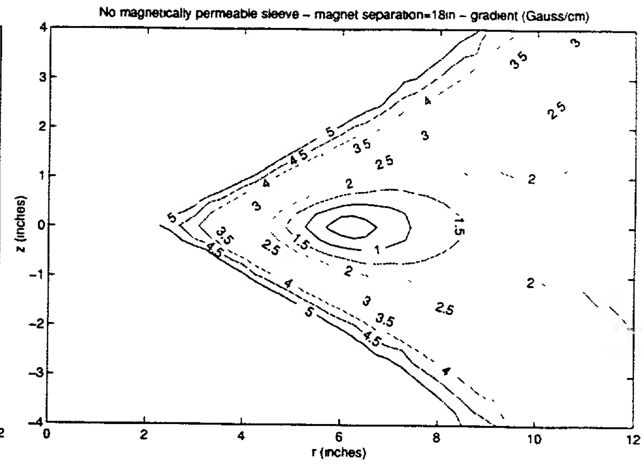


Fig. 3b

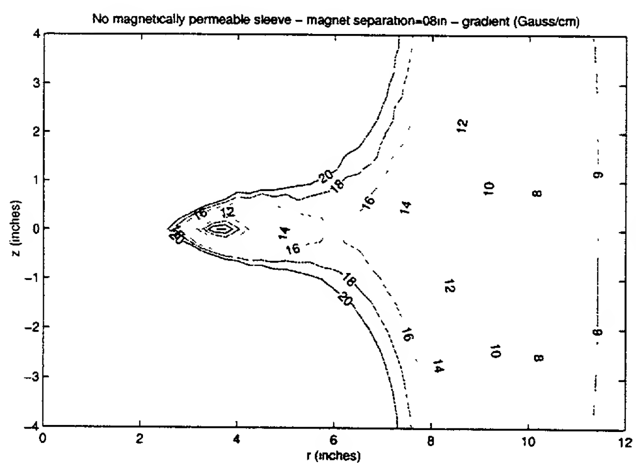


Fig. 3c

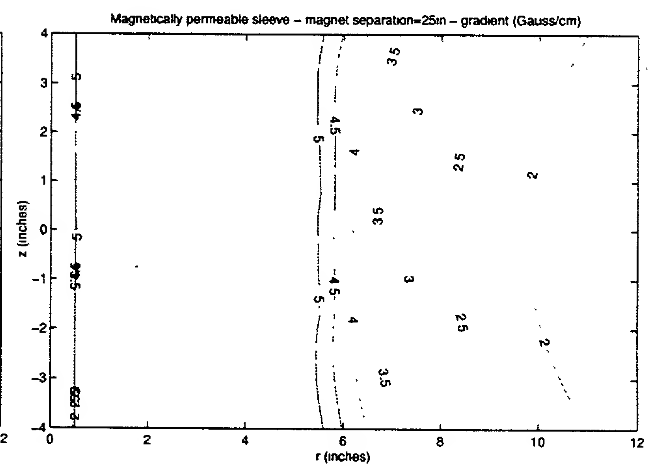


Fig. 3d

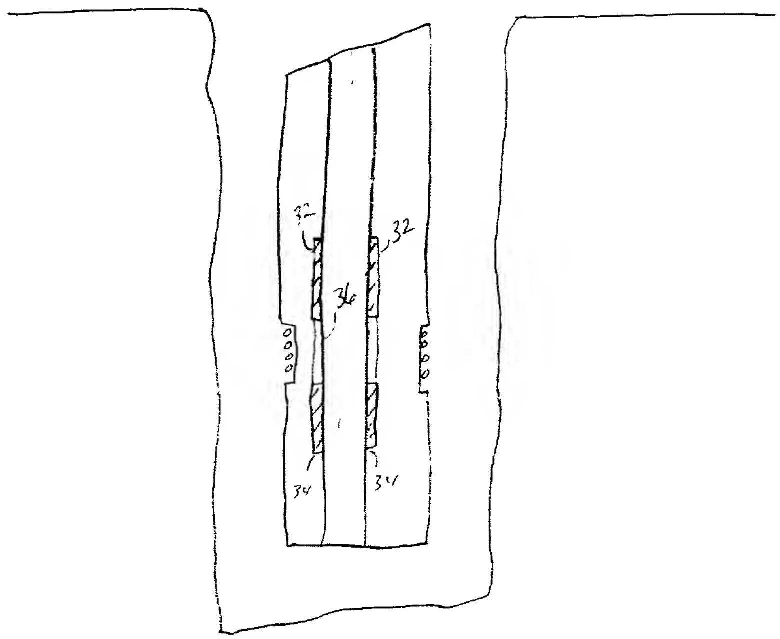


Fig. 4

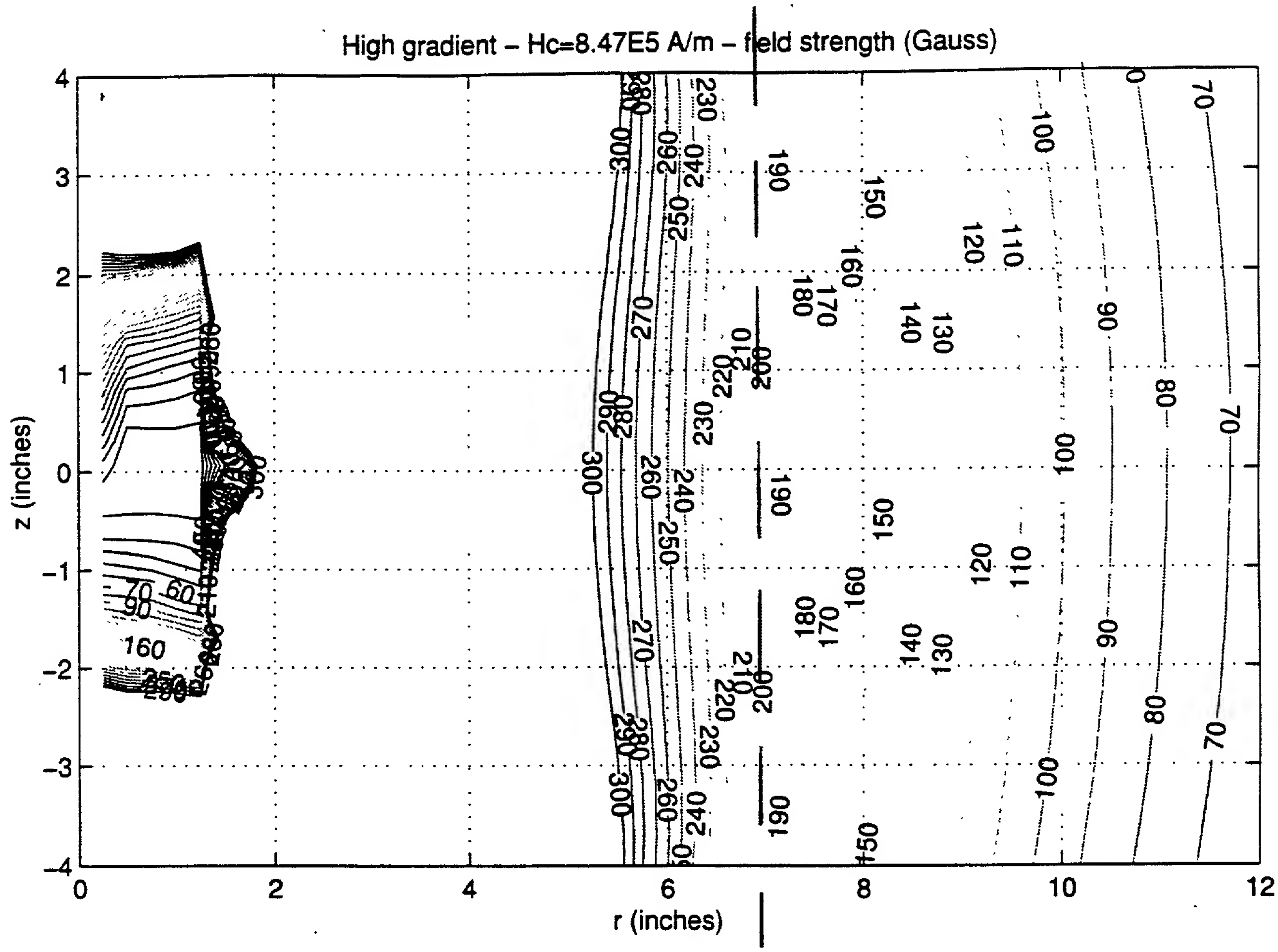
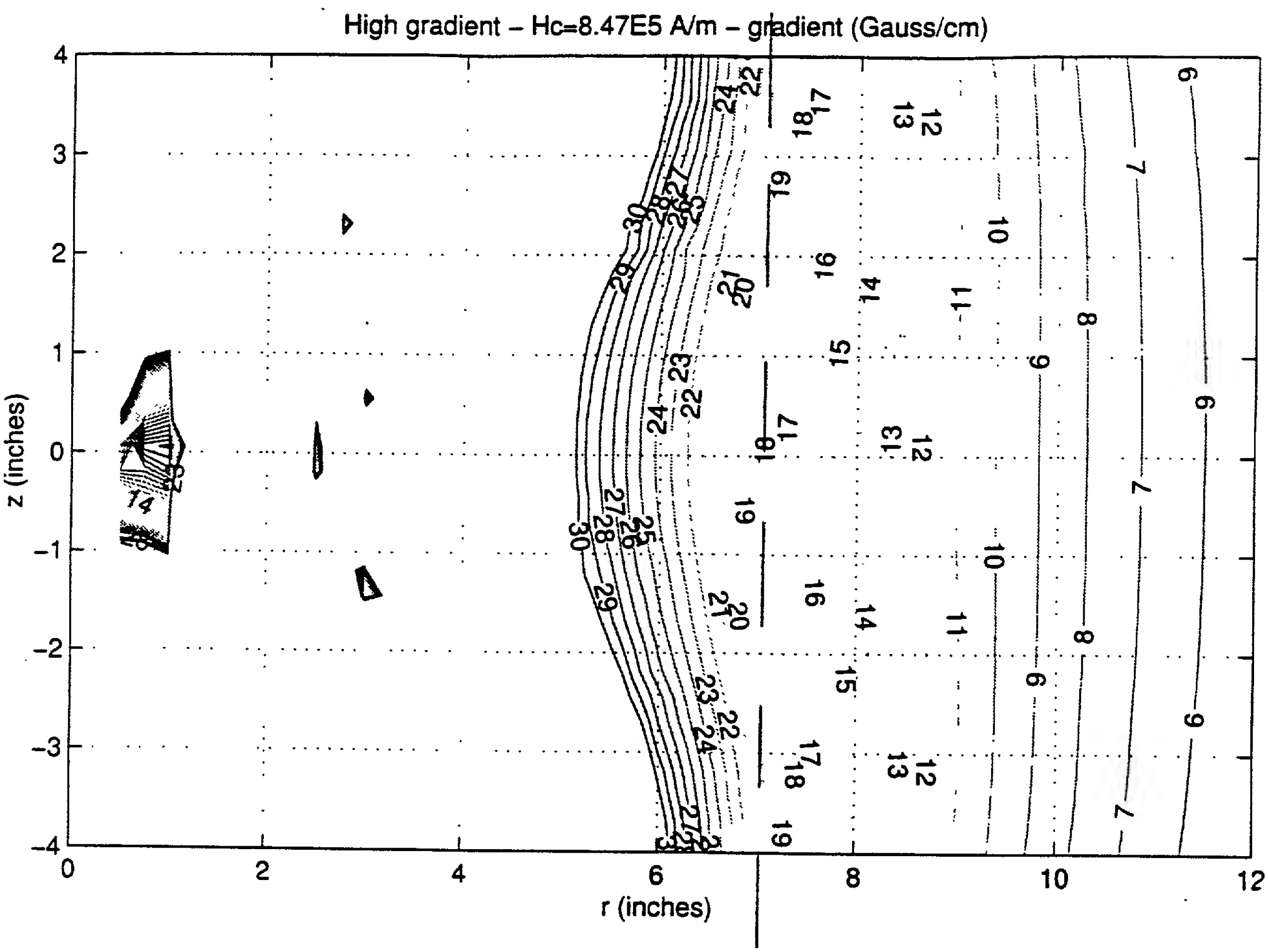

High gradient – Hc=8.47E5 A/m – field strength (Gauss)
z (inches)
r (inches)
300
290
280
270
260
250
240
230
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60

Fig. 4a



High gradient – Hc=8.47E5 A/m – gradient (Gauss/cm)
z (inches)
r (inches)

Fig. 4b

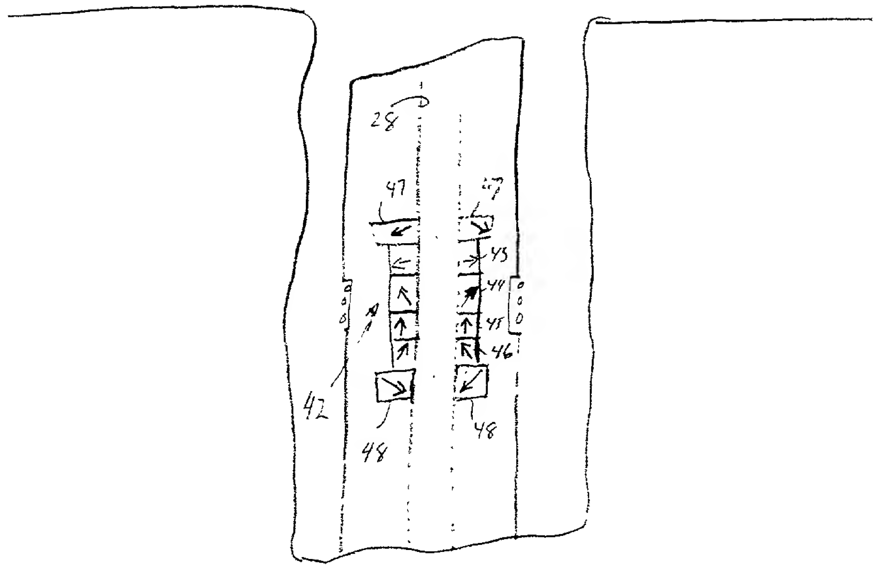


Fig 5

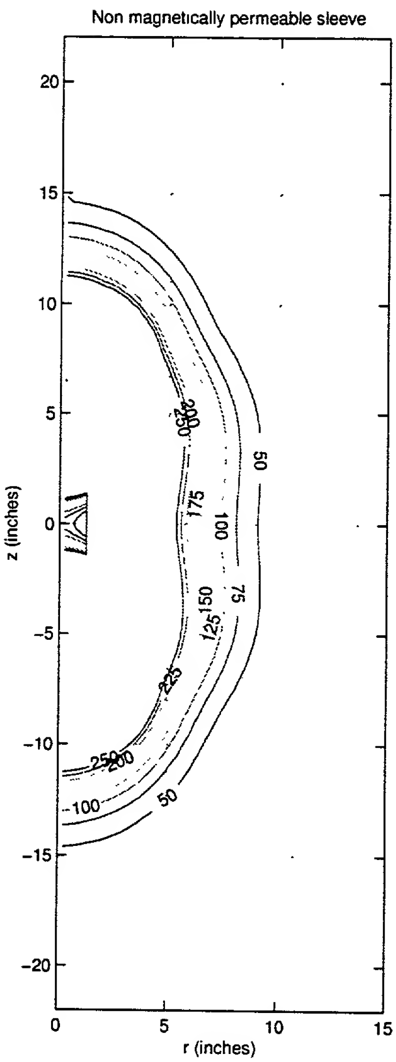

Non magnetically permeable sleeve
z (inches)
r (inches)

Fig 5a

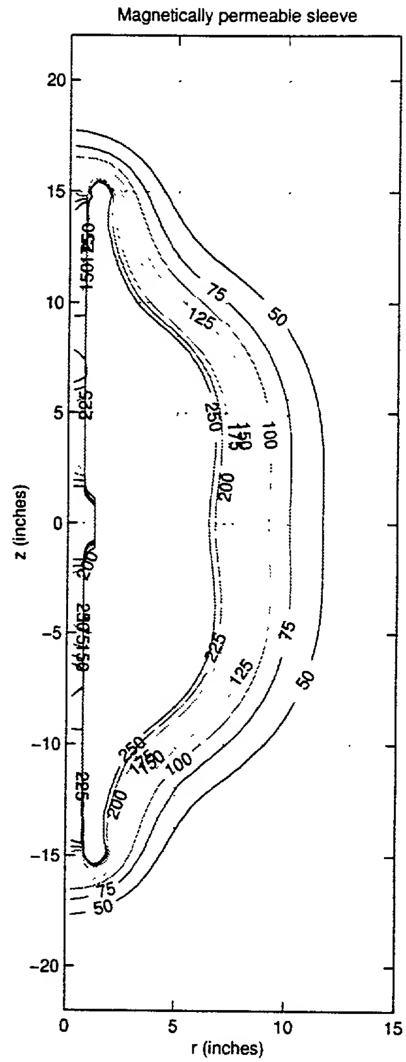

Magnetically permeable sleeve
z (inches)
r (inches)

Fig 5b

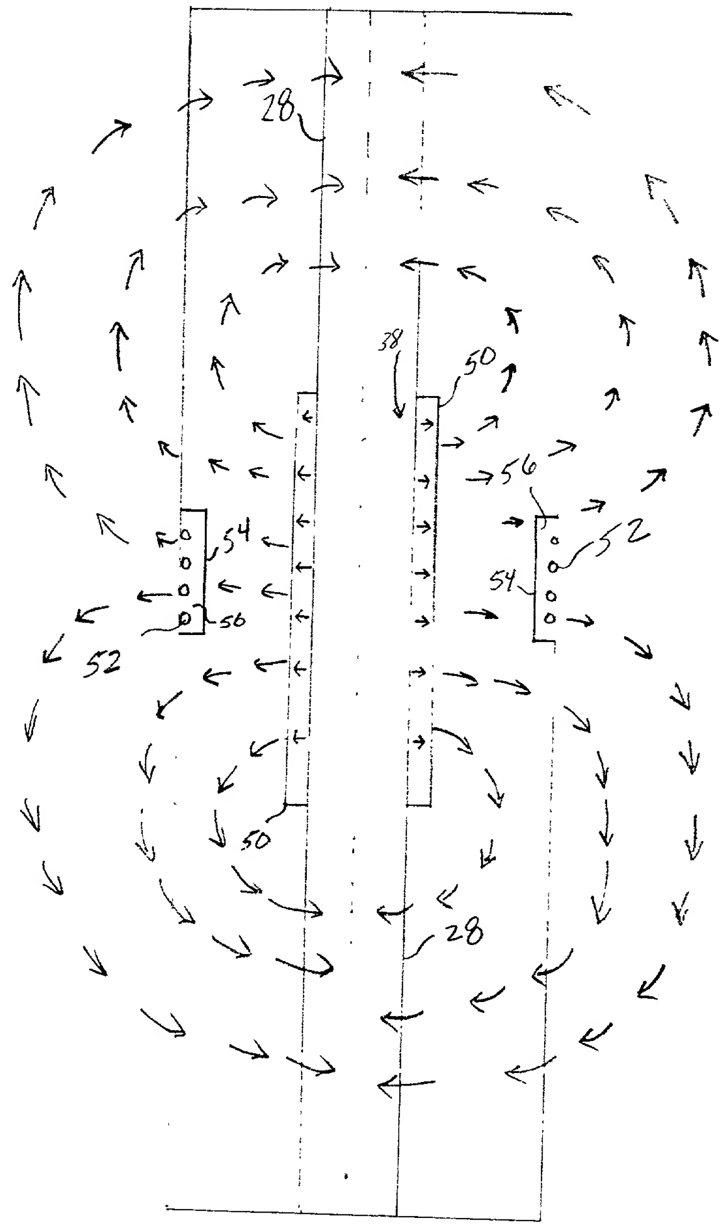


Fig. 6

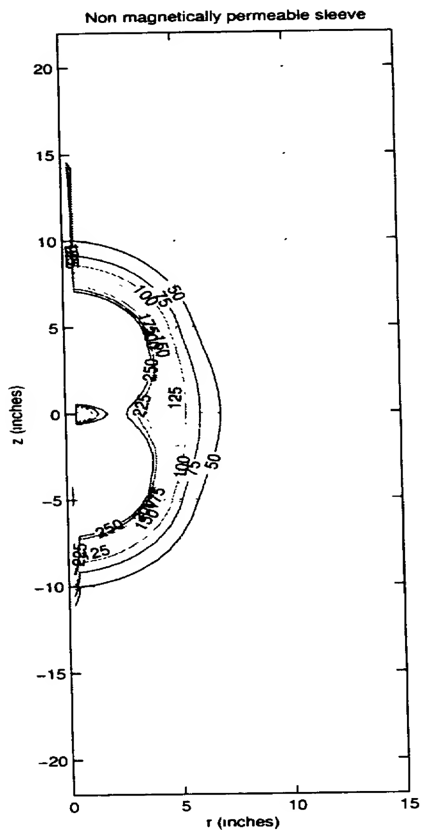

Non magnetically permeable sleeve
z (inches)
r (inches)
20
15
10
5
0
-5
-10
-15
-20
0
5
10
15
50
75
100
125
150
225
250

Fig. 6a

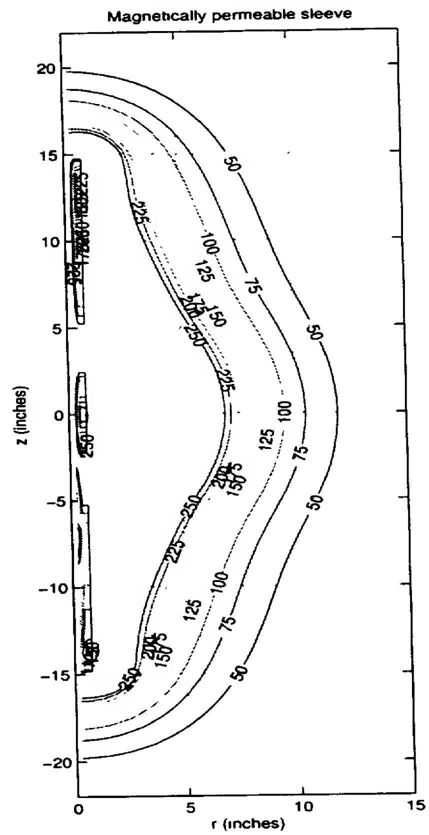

Magnetically permeable sleeve
z (inches)
r (inches)
20
15
10
5
0
-5
-10
-15
-20
0
5
10
15
50
75
100
125
150
175
200
225
250

Fig. 6b

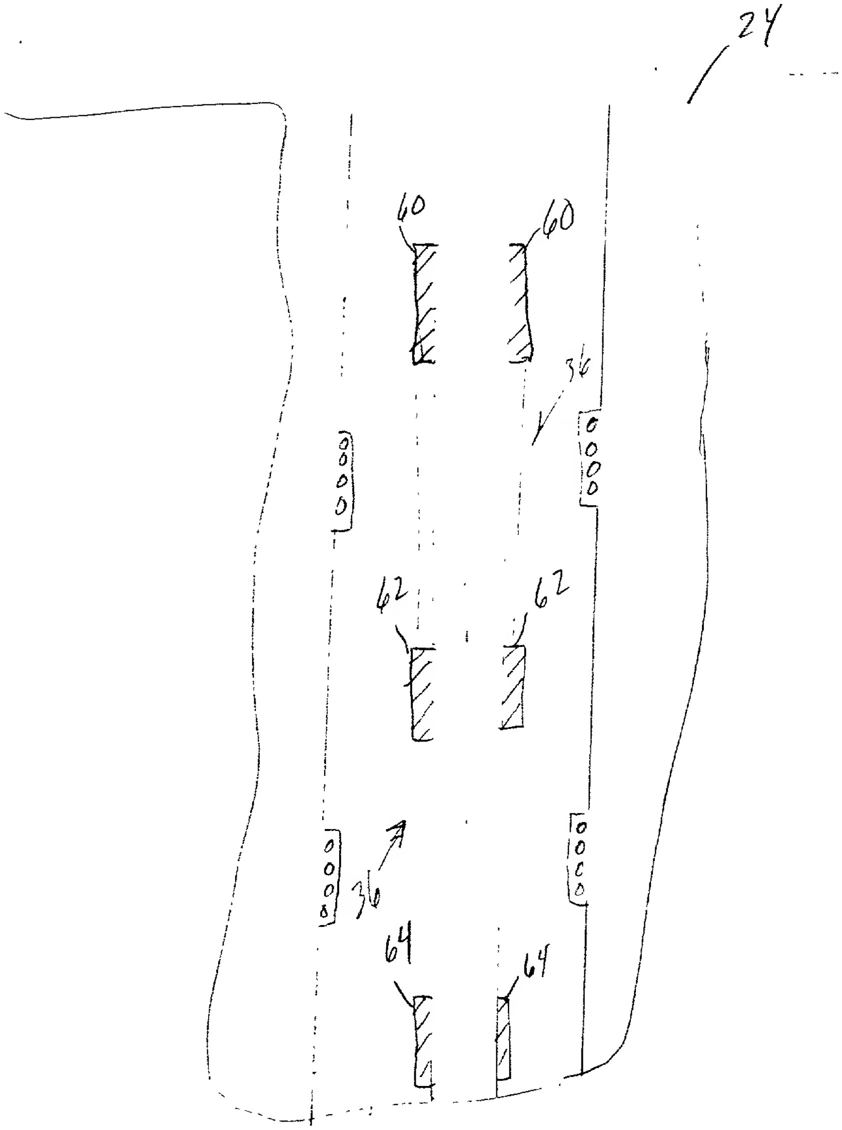


Fig. 7

3–Magnets (μ=150, case No 30) – field strength (Gauss)

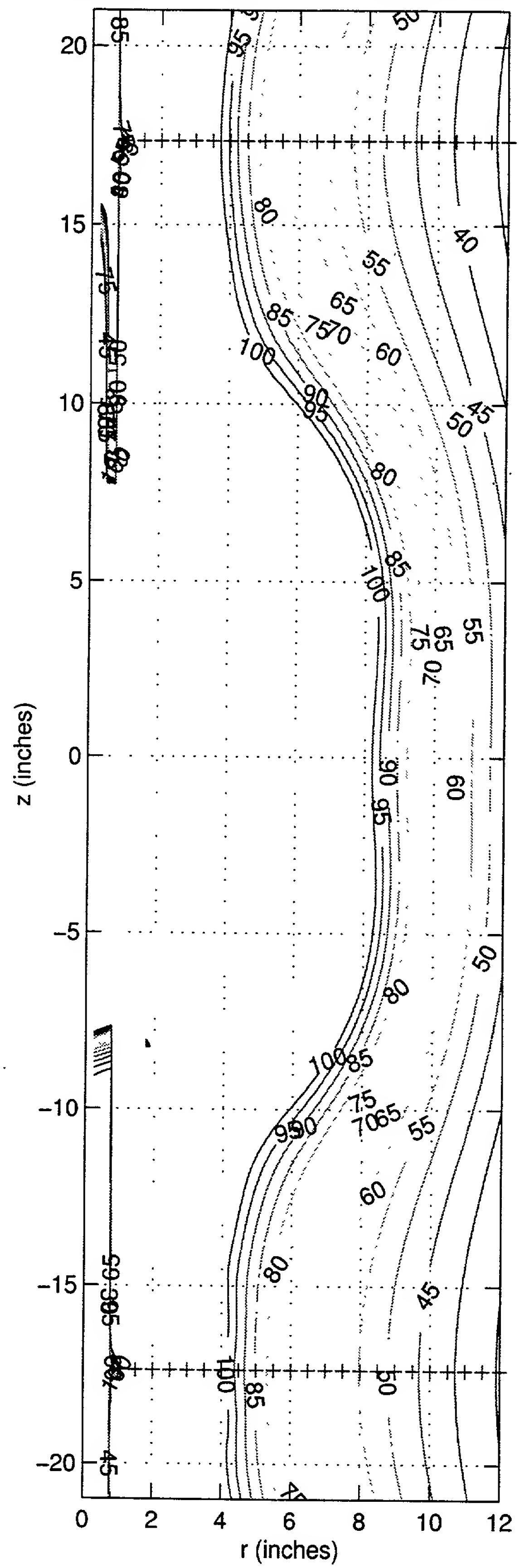


Fig 7a

DECLARATION FOR PATENT APPLICATION AND POWER OF ATTORNEY

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name, and

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled

NUCLEAR MAGNETIC RESONANCE APPARATUS AND METHOD FOR GENERATING A MAGNETIC FIELD HAVING STRAIGHT CONTOUR LINES IN THE RESONANCE REGION

the specification of which

[X] is attached hereto.

[ ] was filed on

as Application Serial Number

and was amended on (if applicable)

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations, Section 1.56(a).

I hereby claim foreign priority benefits under Title 35, United States Code, Section 119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having filing date before that of the application on which priority is claimed:

Prior Foreign Application(s)
Priority Claimed

_______________________ / / / []
YES [ ] NO
(Number) (Country) D/ M/ YR FILED

_______________________ / / / []
YES [ ] NO
(Number) (Country) D/ M/ YR FILED

_______________________ / / / []
YES [ ] NO
(Number) (Country) D/ M/ YR FILED

I hereby claim the benefit under Title 35, United States Code, Section 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in that/those prior application(s) in the manner provided by the first paragraph of Title 35, United States Code, Section 112, I acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, Section 1.56(a) which occurred between the filing date of the prior application and the national or PCT international filing date of this application:

Application Serial No.	Filing Date	Status-patented, pending, abandoned

Application Serial No.	Filing Date	Status-patented, pending, abandoned

As a named inventor, I hereby appoint the following attorney(s) and/or agents(s) to prosecute this application and transact all business in the Patent and Trademark Office connected therewith.

3

J. J. Ryberg, #31,134, Brigitte L. Jeffery, #38,925, Gordon G. Waggett, #34,476. I hereby request that all correspondence, notices, official letters and other communication be directed to Schlumberger Technology Corporation, ATTN: Patent Counsel, P. O. BOX 2175, Houston, Texas 77252-2175; and that all telephone calls be directed to: Brigitte L. Jeffery, at (281) 285 7067, Schlumberger Well Services, P. O. BOX 2175, Houston, Texas 77252-2175.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true, and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

SOLE OR FIRST INVENTOR

Signature Bruno LUONG Date March 3th 1998

Full Name: Bruno Luong 1-00

Residence: 10502 Fountain Lake Drive #1737, Stafford, Texas 77477 USA TX

Citizenship: France

P.O. Address: 10502 Fountain Lake Drive #1737, Stafford, Texas 77477 USA

SECOND INVENTOR

Signature Ganesan Date 3/3/98

Full Name: Krishnamurthy Ganesan 2-00

Residence: 918 Tyler Run, Sugar Land, Texas 77479 USA TX

Citizenship: India

P.O. Address: 918 Tyler Run, Sugar Land, Texas 77479 USA

THIRD INVENTOR

Signature Martin E. Poitzsch Date 3/3/98

Full Name: Martin E. Poitzsch 3-00

Residence: 4807 Periwinkle Court, Sugar Land, Texas 77479 USA TX

Citizenship: United States

P.O. Address: 4807 Periwinkle Court, Sugar Land, Texas 77479 USA